

The Venus Balloon Project Telemetry Processing

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The peculiarities of the Venus Balloon telemetry system required the development of a new methodology for the telemetry processing, since the capabilities of the DSN telemetry system do not include burst processing of short frames with two different bit rates and first bit acquisition. The MDSCC engineering staff was tasked to produce a software package for the non-real time detection, demodulation, and decoding of the telemetry streams obtained from an open loop recording utilizing the DSN spectrum processing subsystem-radio science (DSP-RS). ~~This article contains a~~ general description of the resulting software package (DMO-5539-SP) and its adaptability to the real mission's variations.

I. Introduction

The Venus Balloon telemetry consisted of 330 seconds of 1.67-GHz emissions every 30 minutes, one hour, or two hours, depending on the mission encoder phase. The 330-second emission sequence began with 30 seconds of carrier only (TM1 mode), followed by 270 seconds of telemetry data (TM2 mode), and ended with another 30-second period of carrier only.

During the first 210 seconds, the telemetry data rate was 4 bits/sec, and the last 60 seconds, the rate was 1 bit/sec (see Fig. 1). This telemetry data was convolutionally coded ($K = 6$, $V = 1/2$), and thereafter Manchester encoded with a subcarrier derived from the carrier (1667.9 MHz) divided by 6,553,600, resulting in an approximate subcarrier of 254.5 Hz (see Fig. 2).

The DSN spectrum processing-radio science (DSP-RS) recorded 20K samples/sec sampled spectra on magnetic tapes (level 0). These tapes were processed by DMO-5539-SP (Venus Balloon telemetry software), thus obtaining the decoded data (level 1) tapes.

II. Telemetry Software Description

The telemetry software package ran in a DSN spectrum processing (DSP) environment with three additional peripherals: a local terminal, a hard copy device, and a color display. These peripherals enabled a stand-alone operation isolated from other station activities.

A. Design Criteria

Design parameters were given as (a) signal strength: nominal 18 dB (1 Hz bandwidth), with uncertainty as low as 13 dB; and (b) 1.67 GHz carrier stability:

$$\frac{\Delta f}{f} \cong 10^{-11}$$

The 1.67-GHz carrier uncertainty was estimated in ± 2 kHz, Doppler rate 0.05 Hz/sec. Based on these parameters, the design was concentrated on the detection of weak signals highly stable in frequency and affected by moderate Doppler variations.

Due to the carrier uncertainty, the bandwidth of the radio science open-loop receiver (MMR) analog filter selected was 4091 Hz for frames A-2 to A-6, B-2 to B-46, and A-1 and B-1 (the first frames of every Balloon); when uncertainty was higher, the filter selected was a 8182-Hz bandpass filter. The first Balloon was designated as "A" and the second as "B." Telemetry frames for each Balloon were numbered 1 through 46.

With these constraints in mind, the software was designed with sophisticated algorithms to confirm the presence of the 1.67-GHz carrier under noisy conditions and proved to work satisfactorily with 6 dB less than the nominal case during the compatibility tests with the spacecraft prototype test simulator (PTS). During the real mission, the received signal strength was close to nominal, but the frequency stability and Doppler variations were worse than anticipated by several orders of magnitude. The software was highly modular, and its adaptability to the real situations was relatively simple, although the processing of several "pathological" frames required some interactive operation.

B. Preprocessing

The DSP-RS recorded tapes were selectively transferred to a large capacity disk (LCD) from which the spectrum data was further processed. During this transfer, only 350 seconds of recorded data were copied from the magnetic tape onto the LCDs containing the 330-second emission of the Balloon.

This transfer also performed a 1/2 decimation, reducing the 20K samples/sec to 10K samples/sec. The determination of the MMR filter shape was also possible at this stage. The resulting volume of data to be processed was 3.5 millions of samples (8 bits wide) per Balloon emission.

C. Telemetry Processing

A typical process consisted of the following major steps:

- (1) Carrier confirmation
- (2) Carrier estimation
- (3) Doppler estimation
- (4) Carrier demodulation
- (5) Subcarrier demodulation
- (6) Symbol and frame synchronization
- (7) Viterbi decoding

1. Carrier Confirmation. The purpose of this step was to determine whether a Balloon telemetry frame existed in the recorded data or not. To this end, the carrier confirmation module used 30 seconds of recorded data starting from a

hypothesized carrier-only period, which is to occur in the beginning of each telemetry frame (see Fig. 1).

The process was initiated computing 4096-point FFTs every 0.5 sec of recorded data, thus obtaining 60 power spectra. Then the ten maxima method is applied, forming a histogram from the 60 sets of 10 maxima of each spectrum. In this histogram, the confirmation module may find a zone where n consecutive bins contain a cumulative occurrence of maxima. After an ascending time search of the 60 power spectra, a maxima belonging to that zone satisfying a threshold value ν is a candidate for the searched carrier bin. If m consecutive power spectra contain maxima in the same zone, the presence of carrier is confirmed; if not, the first power spectrum of the set of 60 is discarded, the hypothesized time start is delayed by 0.5 sec, a new FFT is computed for the next 0.5 sec of recorded data, and a new set of 60 power spectra is analyzed with the maxima method. This process is repeated until either the carrier is confirmed or a recording time limit is reached. Figures 3 through 6 illustrate a nominal case and weak signal plots. (Typical values of parameters n , ν , and m were 10, 15 and 2, respectively.)

Once the carrier start time has been determined, the maximum of each of the 60 FFTs is passed to the following module.

2. Carrier Estimation. In this step, the software performs the initial estimation of the carrier frequency and rate using the maxima of the previous step, whenever they correspond to the zone of bins determined there.

Bin numbers are converted to Hertz, thus obtaining the translated 1.66-Hz carrier frequency referenced to the origin of the MMR filter used to condition the DSP-RS discretization process. These frequencies are fitted to a straight line using the least squares method. The resulting regression line provides then the initial estimations of carrier frequency and rate during the first 30 seconds of the Balloon telemetry emission. If the error of a particular point (i.e., its distance to the regression line) is greater than a Δf parameter (typically equal to 5 Hz), then the point is eliminated, and the fitting is repeated.

3. Doppler Estimation. After the initial estimation of carrier frequency and rate obtained in the first 30 seconds of the telemetry transmission by the previous module, the Doppler estimation module worked over the entire 330-second period of the Balloon emission.

In this case, the software algorithm was based on a least squares non-linear regression process with the following model:

$$M_i(t) = A_i \sin(\gamma_i + f_i t + \frac{1}{2} \gamma_i t^2)$$

The model was applied over spans of recorded data with lengths of 10, 4, and 2 seconds, respectively, chosen depending on the observed carrier stability and Doppler rate. In addition to a complete run over the 330 second period, the software was able to be directed to repeat the process on individual spans or groups of variable numbers of spans, with different span lengths or initial parameters.

Each span overlapped the precedent one by 50 percent. The stepping from one span to the next one was based on the SNR of the fitted model; if it violated a pre-established threshold, the model was iterated with a spiral search pattern until the SNR threshold was satisfied. The whole process is detailed in Appendix A, and illustrated in Figs. 7 through 10.

4. Carrier Demodulation. The carrier estimated by the previous module is demodulated from the recorded data samples, S_i , using the following method to maintain phase continuity.

$$S_i = S_i [(1 - \lambda_i) \cos \hat{\omega}_{n-1}(t_i) + \lambda_i \cos \hat{\omega}_n(t_i)]$$

where

$$\lambda_i = \frac{t_i - t_{n-1}}{t_n - t_{n-1}}, \quad n - 1 \leq i < n$$

$$\hat{\omega}_n(t) = \text{carrier estimate in span } n$$

The DC component is removed before and after the demodulation in groups of 5000 samples. After this process, the demodulation samples are reduced from 10K samples/sec to approximately 2500/samples/sec, using a running averages method. The resulting bandwidth is then approximately 1250 Hz.

5. Subcarrier Estimation. The first step in this module is to establish the coherency between the spacecraft timing (in subcarrier cycles) and the ground station timing, from which the data has been synchronized during the sampling and recording by the DSP-RS. Computing the received carrier from the open-loop receiver local oscillator frequency and the translated signal in the MMR filter, we then obtain the actual spacecraft subcarrier frequency by dividing the detected carrier frequency by 6,553,600.

After this frequency is known, the sampled data is arranged so that each subcarrier cycle contains 10 samples, as follows:

$$S_{sci} = \frac{1}{t_s} \int_{t_i}^{t_i} B(t) dt$$

where

S_{sci} = subcarrier sample

$B(t)$ = modulated subcarrier

$$t_s = \frac{\text{sample rate}}{10 \times \text{subcarrier frequency}}$$

From this point on, every pseudosymbol in the last 60 seconds of the telemetry frame contains 640 subcarrier samples, and in the first 210 seconds contains 160 subcarrier samples.

The software now focuses on the last 60 seconds of the telemetry frame, and to estimate the subcarrier phase, uses five subcarrier models with a relative delay of one tenth of a pseudosymbol (i.e., 64 subcarrier samples) and computes the correlation function of the five models in groups of 64 subcarrier samples over the 60 second period of 1 bit/sec (or 4 pseudosymbols/sec) (see Fig. 11). The model of maximum correlation determines the subcarrier phase delay in samples and a first estimation of the pseudosymbol start in tenths of pseudosymbols.

6. Subcarrier Demodulation. The demodulation process is accomplished by taking groups of 10 subcarrier samples (one subcarrier cycle) and inverting the last five, using the subcarrier phase information provided by the previous module. At the same time, a bandwidth reduction is performed averaging the 10-sample groups. The resulting bandwidth is 128 Hz.

7. Symbol Synchronization. This module continues to use the 60 seconds of 1 bit/sec (4 pseudosymbols/sec) to determine the symbol synchronization. The method is based on averaging two half-pseudosymbols (i.e., two groups of 32 samples) centered on the estimated crossing from a positive pseudosymbol to the adjacent negative pseudosymbol.

The difference between the two averages is proportional to the crossing estimation error, which is iteratively corrected until the crossing error is less than or equal to five samples. This process also keeps track of sign transitions to determine the correct pseudosymbol pairing (the two pseudosymbols of the same symbol must have opposite signs.)

The final estimation of the symbol start delay is obtained after computing the pseudosymbol SNRs with a variation of up to 24 samples from the last crossing estimation.

When this symbol synchronization process is completed, the frame is normalized to 16 samples per second (this timing is referred to the spacecraft timing using the determination of the subcarrier coherency in subsection 5). The frame has been now reduced to 5280 samples.

8. Frame Synchronization. The Balloon telemetry frame consists of 900 bits with the following distribution:

48 bits (synch pattern) transmitted at 4 bits/sec

792 bits from 22 measurements of 6 instruments (6 bits each), transmitted at 4 bits/sec

60 bits of 10 data channels (6 bits each), transmitted at 1 bit/sec

The 96 symbols of the frame synch information are contained in 384 samples of the reduced set. This software module looks for the synch pattern correlating the sample set starting at 500 different sample positions around the expected point. The maximum correlation indicates the position of the synch word in the sample set (see Figs. 12 and 13).

From this position, the 1680 symbols corresponding to the 4 bits/sec are computed by removing the Manchester encoding. The 120 symbols corresponding to the 1 bit/sec are obtained in a similar fashion from the remaining samples, averaging four samples per pseudosymbol.

9. Viterbi Decoding. This module performs the convolutional decoding of the 1800-symbol frame using a standard algorithm.

After completing the decoding, the resulting bits are convolutionally encoded to obtain a symbol reference frame, which in turn is used to compute the symbol error distribution. This is presented together with the decoded frame as the end of the overall process.

The analysis of the synch word pattern permits the detection of a data bar condition. Final results are given in data that are true and decommutated (see Fig. 14).

III. Adaptability to the Real Conditions

During the mission, the spacecraft received signal presented the following characteristics:

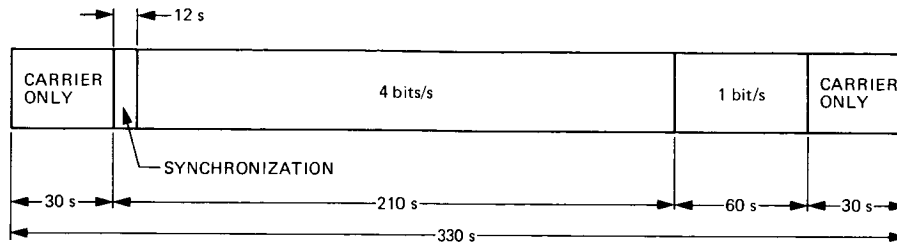
- (1) Average carrier SNR in a 1-Hz bandwidth approximately 20 dB (expected value 18 dB)
- (2) Average symbol SNR approximately 7.5 dB (expected 6.0 dB)
- (3) Frequency variations expected 0.05 Hz/sec
- (4) Frequency variations received up to 3.0 Hz/sec

Frames processed with the antenna near horizon and toward the end of spacecraft battery's lifetime have lower SNR.

The software was able to cope with the above frequency variations after creating new configurations with existing or modified modules and optimizing Doppler estimation parameters. These software modifications resulted in an average degradation of 0.5 dB.

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TM MODE (TELEMETRY)



SYNCHRONIZATION WORD IS FIRST 48 bits

SYNCHRONIZATION WORD: 12 (0), 5 (0), 5 (1), 3 (0), 2 (1), 1 (0), 3 (1), 1 (0),
1 (1), 1 (0), 1 (1), 4 (0), 1 (1), 2 (0), 1 (1), 1 (0),
2 (1), 2 (0)

4 bits/s RESULT IN 16 symbols/s

1 bit/s RESULT IN 4 symbols/s

Fig. 1. Telemetry mode sequence

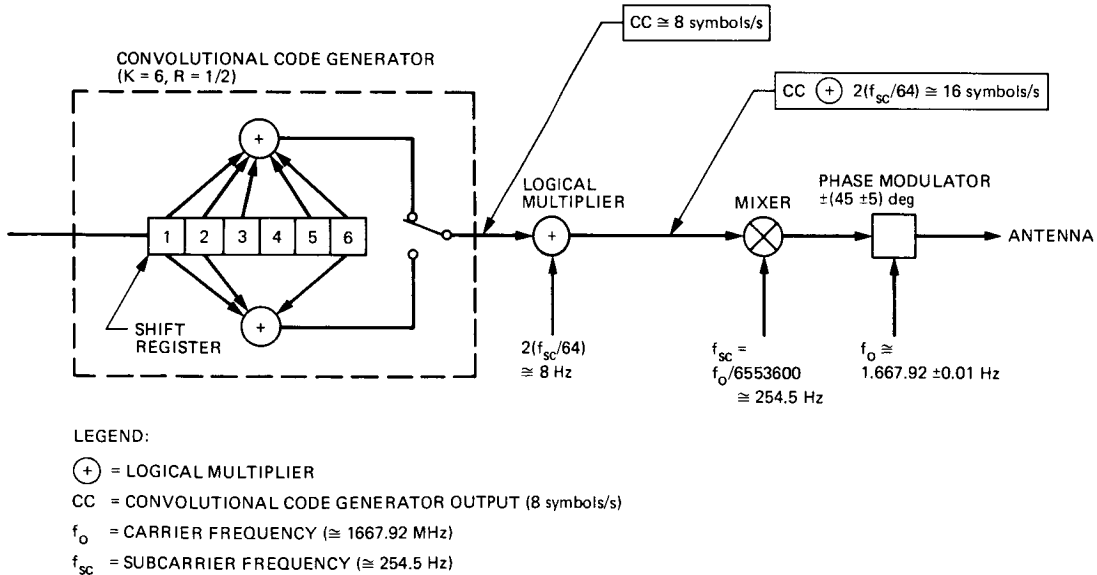


Fig. 2. Telemetry modulation scheme

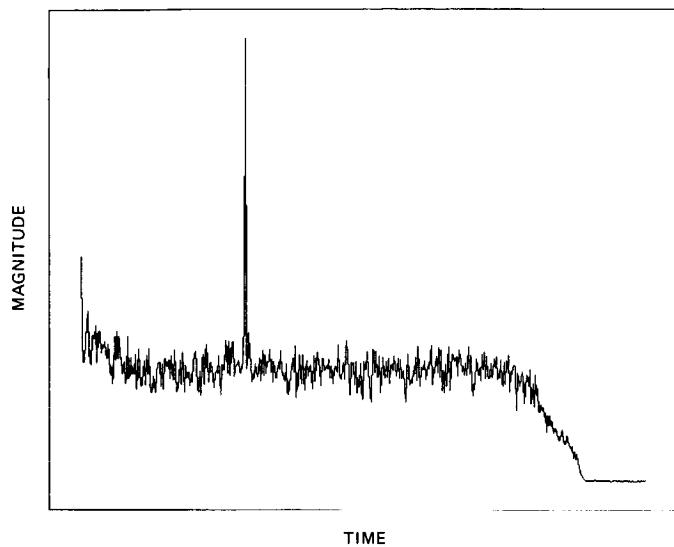


Fig. 3. Carrier detection FFT, nominal signal

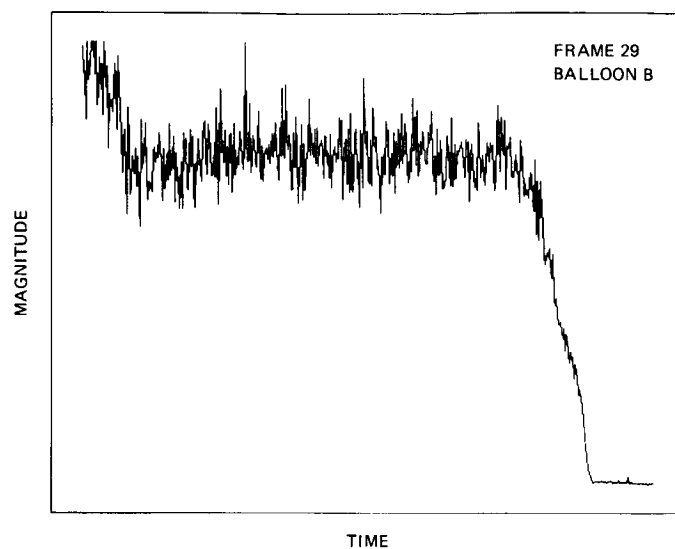


Fig. 5. Carrier detection FFT, weak signal

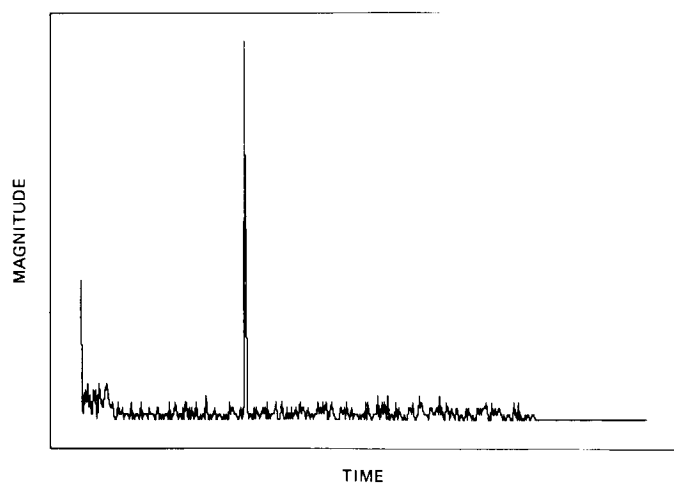


Fig. 4. Carrier detection histogram, nominal signal

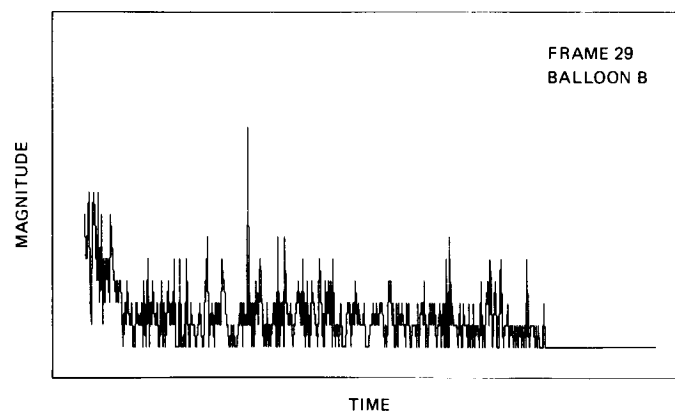


Fig. 6. Carrier detection histogram, weak signal

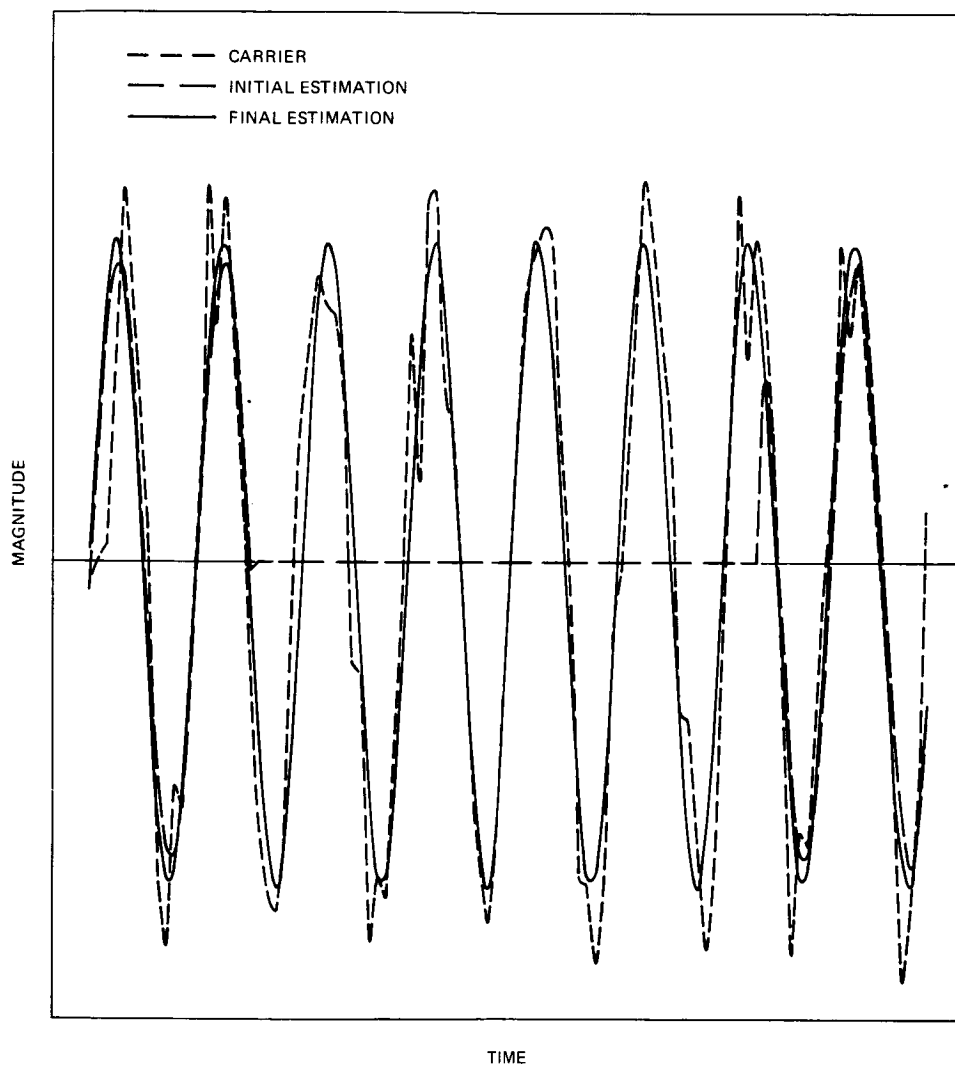


Fig. 7. Doppler estimation, 10 sec span

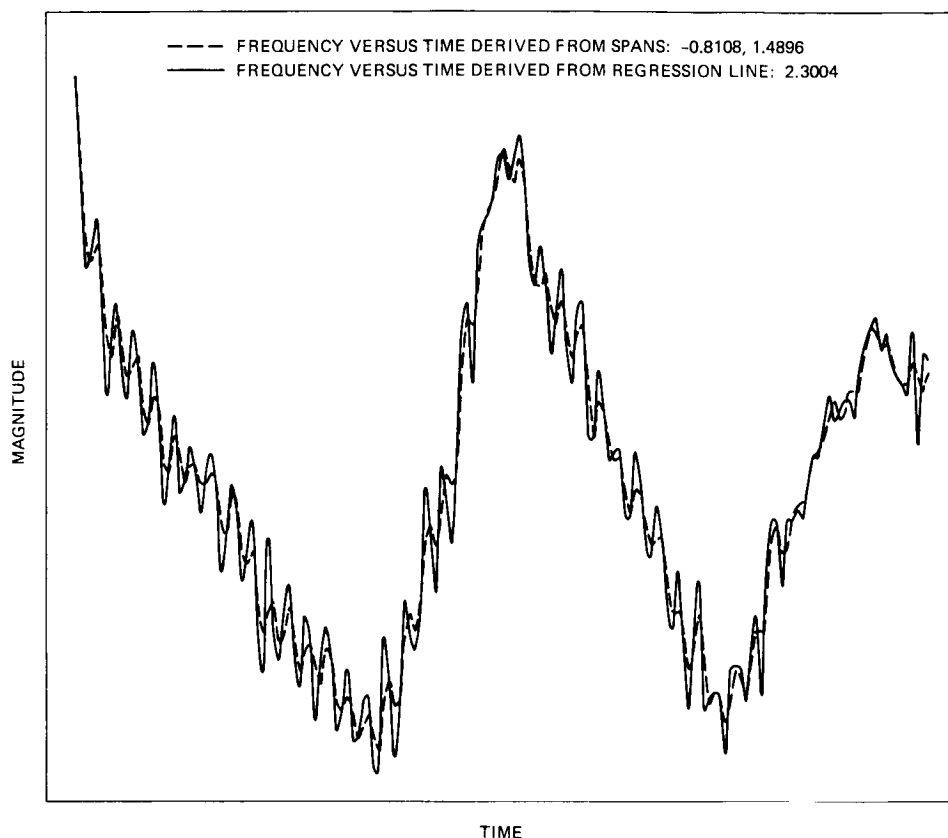


Fig. 8. Carrier frequency vs time (Balloon A2)

TIME	162	4	23	45.80	SPAN	80	PHASE	317.88	FREQ.	1454.15	RATE	-2.6321	AMP.	0.088	SNR	17.00
TIME	162	4	23	46.80	SPAN	81	PHASE	297.11	FREQ.	1450.50	RATE	-0.4855	AMP.	0.092	SNR	17.52
TIME	162	4	23	47.80	SPAN	82	PHASE	81.29	FREQ.	1448.77	RATE	2.1105	AMP.	0.100	SNR	17.99
TIME	162	4	23	48.80	SPAN	83	PHASE	25.79	FREQ.	1450.40	RATE	3.2802	AMP.	0.123	SNR	21.11
TIME	162	4	23	49.80	SPAN	84	PHASE	-7.72	FREQ.	1454.28	RATE	-2.0219	AMP.	0.097	SNR	14.63
TIME	162	4	23	50.80	SPAN	85	PHASE	-21.18	FREQ.	1457.71	RATE	-0.7964	AMP.	0.101	SNR	14.72
TIME	162	4	23	51.80	SPAN	86	PHASE	63.95	FREQ.	1458.10	RATE	-3.1915	AMP.	0.082	SNR	16.22
TIME	162	4	23	52.80	SPAN	87	PHASE	216.56	FREQ.	1455.21	RATE	-3.7863	AMP.	0.092	SNR	18.84
TIME	162	4	23	53.80	SPAN	88	PHASE	16.68	FREQ.	1450.52	RATE	-2.0800	AMP.	0.089	SNR	17.11
TIME	162	4	23	54.80	SPAN	89	PHASE	283.68	FREQ.	1447.10	RATE	0.2466	AMP.	0.076	SNR	16.14

Fig. 9. Partial listing of Doppler estimation (Balloon A4)

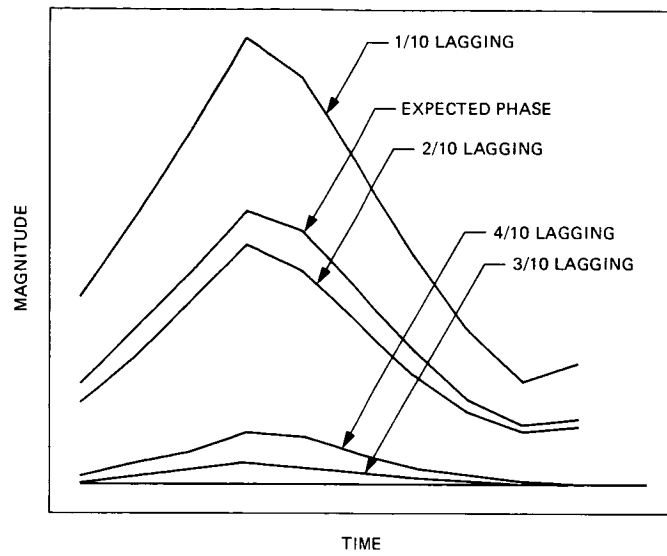


Fig. 10. Subcarrier and symbol correlations

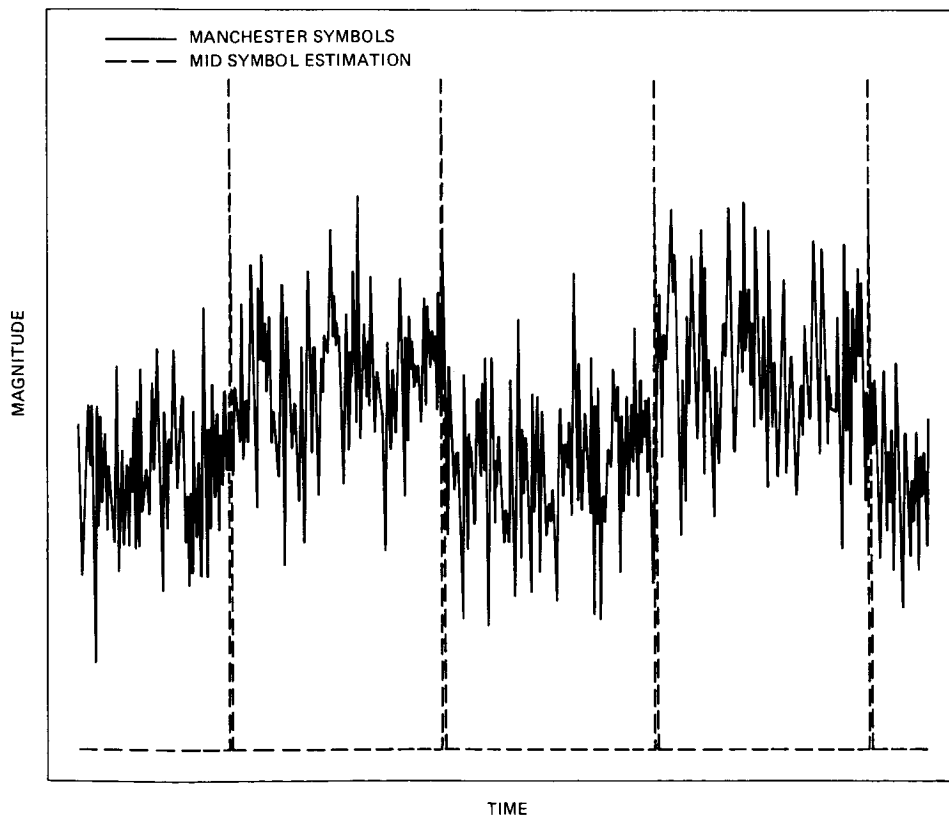


Fig. 11. Mid-symbol estimations

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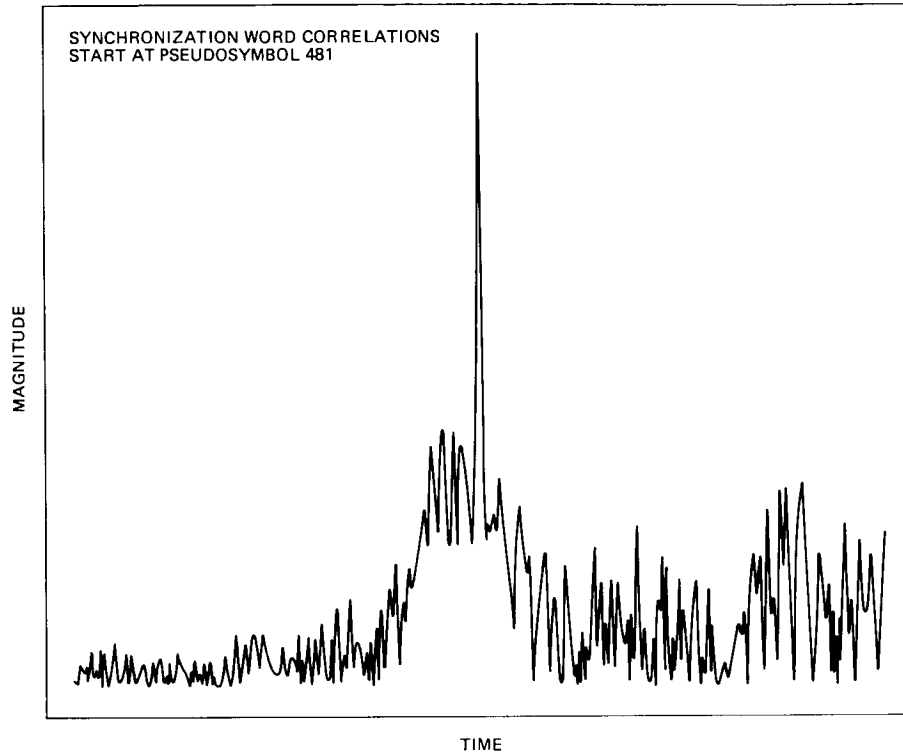


Fig. 12. Frame synch word detection

- DECOMMUTATED DATA -

RECORDING	163	4	30	54.80
SYNC WORD AT	163	4	31	29.38

FRAME SYNC : 0 7C6E A12C

1	0	7	5	8	31	1C	0	13	20	7	6	8	1F	3A	0
2	10	7	3	38	24	2C	2	14	10	7	5	29	1F	39	0
3	0	7	5	9	2E	4	0	15	30	7	3	39	11	9	0
4	20	7	5	28	29	C	0	16	30	7	4	6	1C	39	0
5	10	7	3	19	1F	3C	0	17	0	7	2	17	22	9	0
6	20	7	6	9	15	1C	0	18	10	7	4	18	1D	19	0
7	20	7	4	6	15	2B	0	19	10	7	3	29	14	4	0
8	30	7	5	17	1F	1C	0	20	20	7	10	30	1C	15	0
9	10	7	0	17	5	1C	0	21	1C	1F	37	0	1C	17	0
10	10	7	5	3	3A	7	0	22	F	25	37	0	1C	12	1
11	0	7	2A	9	2F	24	0	23	9	3D	1A	0	1E	2C	0
12	20	7	3	1E	F	1A	0	24	27	3A	12	0	0	0	0

- SYMBOL ERROR RATE = 0.00168

Fig. 13. Decommuted frame

Appendix A

Doppler Estimation Span Processing

The received signal (PCM/PSK/PM) can be represented mathematically by (Refs. A-1, A-2):

$$S(t) = \sqrt{2P} (\sin \omega(t) \cos \theta + \cos \omega(t) \sin \theta B(t))$$

This signal is mixed with a local estimate:

$$S_m(t) = \cos \hat{\omega}(t)$$

and the result, after a low pass filter provides S_i samples that are a function of the difference $\omega - \hat{\omega}$. The process is as follows.

Mixing (see Fig. A-1):

$$\begin{aligned} S(t) \cdot S_m(t) &= \sqrt{2P} (\sin \omega(t) \cos \theta + \cos \omega(t) \sin \theta B(t)) \\ &\quad \times \cos \hat{\omega}(t) \\ &= \sqrt{2P} \left[\frac{1}{2} (\sin (\omega(t) - \hat{\omega}(t)) \cos \theta + \frac{1}{2} \right. \\ &\quad \times (\sin (\omega(t) + \hat{\omega}(t)) \cos \theta) \\ &\quad + \sqrt{2P} \left[\frac{1}{2} ((\cos (\omega(t)) - \hat{\omega}(t) + (\cos (\omega(t) \right. \\ &\quad \left. + \hat{\omega}(t))) \sin \theta B(t)) \right] \end{aligned}$$

Filtering:

$$S_i = \int_{t-\Delta t/2}^{t+\Delta t/2} S(t) \cdot S_m(t) dt$$

This filter cancels terms with $(\omega(t) + \hat{\omega}(t))$ and terms with $B(t)$, resulting in:

$$S_i = \frac{\sqrt{2P}}{2} \sin [\omega(t) - \hat{\omega}(t)] \cos \theta$$

and calling:

$$A = \frac{\sqrt{2P}}{2} \cos \theta$$

$$\omega_D(t) = \omega(t) - \hat{\omega}(t) = \psi + f t + \frac{1}{2} \gamma t^2$$

The problem now is to minimize

$$\sum (S_i - M_i)^2$$

Since S_i is equal to the reduced sample set

$$M_i = A \sin (\omega_D(t_i)) = A \sin \left(\psi + f t_i + \frac{1}{2} \gamma t_i^2 \right)$$

that is equivalent to solving the non-linear system:

$$-2 \sum (S_i - M_i) \frac{\gamma M_i}{\gamma X_k} = 0$$

where

$$1 \leq k \leq 4$$

$$x_1 = A$$

$$x_2 = \psi$$

$$x_3 = f$$

$$x_4 = \gamma$$

Expanding this expression, we obtain the system in explicit form:

$$\left. \begin{aligned} \sum_i (S_i - A \sin \omega_d(t_i)) \sin \omega_d(t_i) &= 0 \\ \sum_i (S_i - A \sin \omega_d(t_i)) A \cos \omega_d(t_i) &= 0 \\ \sum_i (S_i - A \sin \omega_d(t_i)) A t \cos \omega_d(t_i) &= 0 \\ \sum_i (S_i - A \sin \omega_d(t_i)) \frac{A t^2}{2} \cos \omega_d(t_i) &= 0 \end{aligned} \right\}$$

After sample trigonometric operations, the system is expressed with the following non-linear functions: $\sin \omega_d$, $\cos \omega_d$, $A \sin 2\omega_d$, $A \cos 2\omega_d$. This non-linear system is linearized to approximate the above functions by their Taylor series expansions.

After establishing a linear system of four equations with four unknowns (ψ, f, γ, A), the solution is obtained by iteration from a starting point ($\psi_0, f_0, \gamma_0, A_0$). Iteration increments for f and γ are obtained in a spiral way (see Fig. A-2), where negative values of f are avoided.

Limits of the spiral way are:

$$f \geq 0, |f - f_b| \leq f_{lim} \quad |\gamma| \leq \gamma_{lim} \quad f + t_s \gamma \leq BW$$

where

$$t_s = \text{span length in seconds}$$

BW = low pass filter bandwidth

Typical values are: $f_b = 0.8$ Hz, $f_{lim} = 0.8$ Hz, $\gamma_{lim} = 0.05$ Hz/sec. The initial values for the other two unknowns are:

$$A_0 = \frac{\sqrt{2}}{N} \sum_i^N |S_i|$$

(initial amplitude)

$$\psi_0 = K \psi_{20}$$

with K such that it maximizes:

$$\left| \sum_i^N S_i \sin \left(K \psi_{20} + f_0 t_i + \frac{1}{2} \gamma_0 t_i^2 \right) \right|$$

for $1 \leq K \leq 18$ and ψ_{20} = phase corresponding to the first step of 20 degrees.

The iteration process is started with an initial vector:

$$X_0 = (\psi_0, f_0, \gamma_0, A_0)$$

and an incremental vector:

$$\Delta X_0 = (\Delta \psi_0, \Delta f_0, \Delta \gamma_0, \Delta A_0)$$

in the usual way:

$$\begin{aligned} X_1 &= X_0 + \Delta X_0 \rightarrow \Delta X_1 \\ &\vdots \\ X_N &= X_{N-1} + \Delta X_{N-1} \rightarrow \Delta X_N \end{aligned}$$

The process finishes when:

$$|\Delta X_{NK}| \leq 10^{-5}, \quad 1 \leq k \leq 4$$

If this limit is not reached, the sequence is aborted when N is greater than the other limit (typically 60). Then, new initial values are obtained from the spiral search and the process is resumed.

If the convergence to 10^{-5} is obtained, a carrier SNR is computed and tested against a threshold value. If the test passes, this vector (ψ, f, γ, A) is considered a valid solution. If the test fails, the process is repeated with new initial values from the spiral search until a solution is found, or the spiral way is exhausted. When the latter happens, the solution with higher SNR is adopted.

Multiplicity of Solutions: If (ψ, f, γ, A) is a solution, ($-\psi, -f, -\gamma, -A$) and ($\psi_{+N}, -f, -\gamma, A$) are possible solutions that must be discarded. The set ($-\psi, -f, -\gamma, -A$) is easily detected by checking the sine of the amplitude (A). The set ($\psi_{+N}, -f, -\gamma, A$) is avoided by mixing with a frequency lower than the one estimated (typically 0.8 Hz lower), so that after mixing the difference will always be positive.

References

- A-1. Yuen, J. H., *Deep Space Telecommunications Systems Engineering*, Jet Propulsion Laboratory, Pasadena, Calif., 1982.
- A-2. Lindsey, W. C., and Simon, M. K., *Telecommunications Systems Engineering*, Englewood Cliffs, N.J.: Prentice-Hall, 1973.

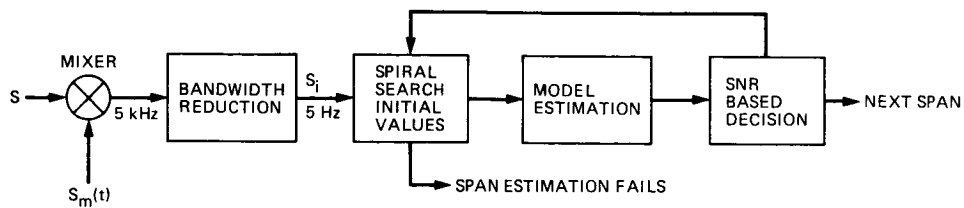


Fig. A-1. Doppler estimation span processing

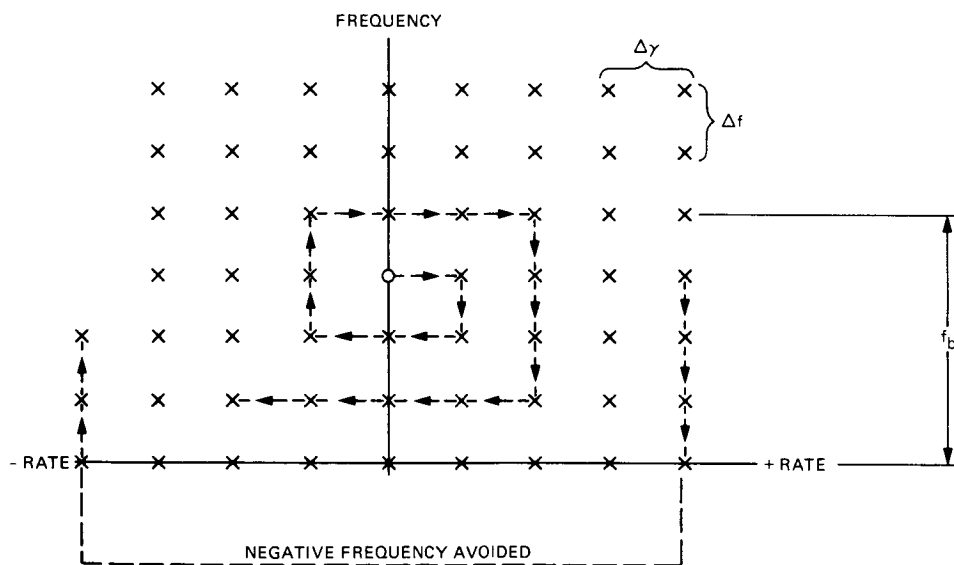


Fig. A-2. Spiral searching